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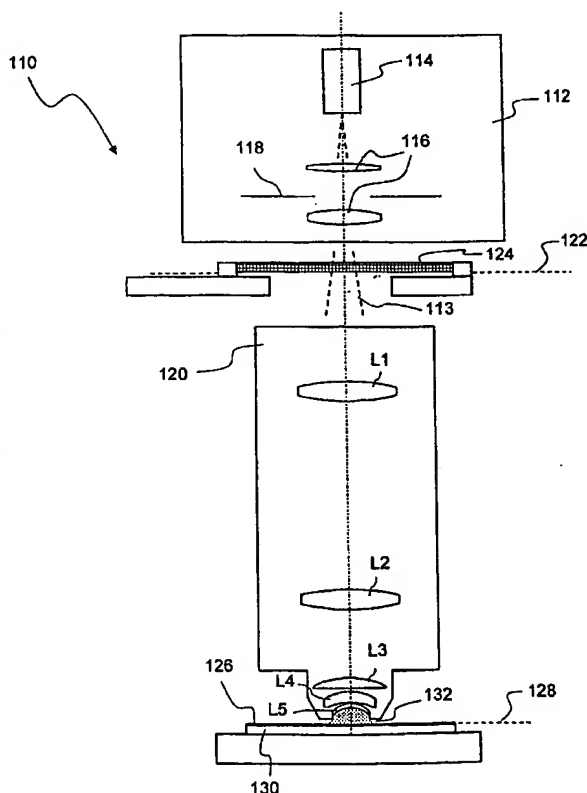
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(54) Title: PROJECTION OBJECTIVE FOR A MICROLITHOGRAPHIC PROJECTION EXPOSURE APPARATUS



(57) Abstract: A projection objective of a microlithographic projection exposure apparatus (110) is designed for immersion operation in which an immersion liquid (134) adjoins a photosensitive layer (126). The refractive index of the immersion liquid is greater than the refractive index of a medium (L5; 142; L205; LL7; LL8; LL9). that adjoins the immersion liquid on the object side of the projection objective (120; 120'; 120''). The projection objective is designed such that the immersion liquid (134) is convexly curved towards the object plane (122) during immersion operation.

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PROJECTION OBJECTIVE FOR A
MICROLITHOGRAPHIC PROJECTION EXPOSURE APPARATUS

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BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to microlithographic projection exposure apparatuses as are used to manufacture large-scale integrated electrical circuits and other microstructured components. More particular, the invention relates to a projection objective of such an apparatus that is designed for immersion operation.

2. Description of Related Art

10 Integrated electrical circuits and other microstructured components are normally produced by applying a plurality of structured layers to a suitable substrate, which may be, for example, a silicon wafer. To structure the layers, they are first covered with a photoresist that is
15 sensitive to light of a certain wavelength range. The wafer coated in this way is then exposed in a projection exposure apparatus. In this operation, a pattern of structures contained in a mask is imaged on the photoresist with the aid of a projection objective. Since the
20 imaging scale is generally smaller than 1, such projec-

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tion objectives are frequently also referred to as reduction objectives.

After the development of the photoresist, the wafer is subjected to an etching or deposition process, as a result of which the uppermost layer is structured in accordance with the pattern on the mask. The photoresist still remaining is then removed from the remaining parts of the layer. This process is repeated until all the layers have been applied to the wafer.

One of the most prominent objects in the design of projection exposure apparatuses is to be able to define lithographically structures having increasingly smaller dimensions on the wafer. Small structures result in high integration densities, which generally have a favorable effect on the performance of the microstructured components produced with the aid of such apparatuses.

One of the most important parameters that determine the minimum size of the structures to be lithographically defined is the resolution of the projection objective. Since the resolution of the projection objectives decreases as the wavelength of the projection light becomes smaller, one approach to achieve smaller resolutions is to use projection light with ever-shorter wavelengths. The shortest currently used wavelengths are in the deep ultraviolet (DUV) spectral range and are 193 nm and 157 nm.

Another approach to decrease the resolution is to introduce an immersion liquid having high refractive index into the gap that remains between a final lens element on the image side of the projection objective and the photo-
5 resist or another photosensitive layer to be exposed. Projection objectives that are designed for immersion operation and are therefore also referred to as immersion objective may reach numerical apertures of more than 1, for example 1.3 or 1.4. The term "immersion liquid"
10 shall, in the context of this application, relate also to what is commonly referred to as "solid immersion". In the case of solid immersion, the immersion liquid is in fact a solid medium that, however, does not get in direct contact with the photoresist but is spaced apart from it by
15 a distance that is only a fraction of the wavelength used. This ensures that the laws of geometrical optics do not apply such that no total reflection occurs.

Immersion operation, however, does not only allow to achieve very high numerical apertures and, consequently,
20 a smaller resolution, but it also has a favorable effect on the depth of focus. The higher the depth of focus is, the lower are the requirements imposed on an exact positioning of the wafer in the image plane of the projection objective. Apart from that, it has been found out that
25 immersion operation considerably relaxes certain design constraints and simplifies the correction of aberrations if the numerical aperture is not increased.

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In the meantime, immersion liquids have been developed whose refractive index is significantly above that of de-ionized water ($n_{H_2O} = 1.43$) and that are nevertheless also highly transparent and resistant to projection light of the wavelength 193 nm. When using immersion liquids with such high refractive indices, it may happen that the refractive index of the immersion liquid is greater than the refractive index of the material of which the last optical element on the image side is composed. In conventional projection objectives having a last optical element with a plane surface on the image side, the maximum numerical aperture is restricted by the refractive index of this last optical element. If this optical element is, for example, made of quartz glass, an increase in the numerical aperture beyond the refractive index of quartz glass ($n_{SiO_2} = 1.56$) is not possible although the refractive index of the immersion liquid is even higher.

Document JP 2000-058436 A discloses a projection exposure apparatus having a projection objective can be used both in dry and in immersion operation. When switching to immersion operation, an additional lens element having a concave surface on the image side is introduced into the gap between the last optical element of the projection objective and the wafer. The interspace between the additional lens element and the wafer may be filled with an immersion liquid, for example an oil. This document does not disclose the refractive indices of the immersion liquid and the additional lens element.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide an immersion projection objective in which the refractive index of the last optical element on the image side is larger is smaller than the refractive index of the immersion liquid, but having a numerical aperture that is not restricted by the refractive index of the last optical element.

This object is achieved in that, during immersion operation, the immersion liquid is convexly curved towards the object plane.

As a result of the convex curvature of the immersion liquid towards the object plane, the angles of incidence at which projection light rays impinge on the interface between an adjoining medium, e.g. the last optical element on the image side, and the immersion liquid are reduced. Thus a light ray that would be totally reflected by a flat interface can now contribute to the image, and this, in turn, allows higher numerical apertures that can also be above the refractive index of the last optical element on the image side. In this way the numerical aperture is limited only by the refractive index of the immersion liquid, but not by the refractive index of the medium that adjoins the immersion liquid on the object side.

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The simplest way of achieving an immersion liquid that is convexly curved towards the object plane is to allow the immersion liquid to adjoin directly a concavely curved image-side surface of the last optical element of the projection objective. The curvature of the immersion liquid is then unalterably fixed by the curvature of this surface.

In order to prevent an undesired drainage of the immersion liquid from the cavity that is formed by the concavely curved image-side surface of the last optical element, this surface may be surrounded circumferentially by a drainage barrier. This may, for example, be a ring that is joined to the last optical element and/or a housing of the projection objective. The ring, which may be composed, for example, of a standard lens material such as quartz glass or calcium fluoride (CaF_2), but also of a ceramic or of hardened steel, is preferably provided on the inside with a coating that prevents contamination of the immersion liquid by the ring. Such a ring is also advantageous if the refractive index of the immersion liquid is equal to or smaller than the refractive index of the medium that adjoins the immersion liquid on the object side.

The image-side surface of the last optical element may be spherical. Calculations have shown that the radius of curvature may advantageously be selected to be between 0.9 times and 1.5 times and preferably 1.3 times the ax-

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ial distance (i.e. vertex distance) between the this surface and the image plane. Such a configuration, which is also advantageous if the refractive index of the immersion liquid is equal to or smaller than the refractive index of the medium that adjoins the immersion liquid on the object side, has the advantage the high angles of incidence at the object side interface of the immersion liquid are avoided. Such high angles usually result in a strong sensitivity of the interface to design and manufacturing deficiencies. From this point of view, the angles of incidence should be as small as possible. This generally requires a very large curvature (i.e. a small radius of curvature) of the object-side interface of the immersion liquid.

Another way of obtaining an interface of the immersion liquid that is convexly curved toward the object plane is to introduce an intermediate liquid between the last optical element and the immersion liquid. This intermediate liquid is not miscible with the immersion liquid and forms a curved interface in an electric field during immersion operation. Such a configuration is also advantageous if the refractive index of the immersion liquid is equal to or smaller than the refractive index of the medium that adjoins the immersion liquid on the object side.

This approach makes use of an effect that is also known as "electrowetting". If the magnitude of the electric

field is altered, this is accompanied by an alteration in the curvature of the interface. This effect has hitherto been used, however, only for autofocus lenses for CCD or CMOS sensors on components that are produced by Variop-
5 tic, France.

The more the electrical conductivities of the two liquids differ from one another, the greater is the curvature of the interface. A large difference may be achieved if one of the two liquids, for example the intermediate liquid,
10 is electrically conductive and the other liquid, for example the immersion liquid, is electrically insulating.

It is furthermore advantageous if the intermediate liquid has substantially the same density as the immersion liquid since no buoyancy forces can occur and, consequently,
15 the shape of the interface is independent of the position of the arrangement in space.

The refractive index of the intermediate liquid should be less than the refractive index of the immersion liquid, but it may be less or greater than the refractive index
20 of the last optical element on the image side.

Preferably, the electric field that is necessary to form the curved interface is generated by an electrode. A symmetrical formation of the interface can be achieved, for example, by using an annular cone electrode that is dis-
25 posed between the last optical element and the image

plane. The curvature of the interface can be continuously varied in this way by varying a voltage applied to the electrode. This can be exploited in order to correct certain imaging properties of the projection objective.

5 Above it has been mentioned that it may be desirable to have a strongly curved interface between the immersion liquid and the medium adjoining to the object side, because this simplifies the correction of imaging aberrations. However, it has also significant advantages if the
10 curvature of this interface is small. This is because a large curvature generally leads to the formation of a cavity within the last optical element. Such a cavity has several drawbacks. For example, it favors the occurrence of undesired turbulences within the cavity if a flow of
15 the immersion liquid has to be maintained, for example for reasons of temperature stability and for purifying the liquid. Furthermore, highly refractive immersion liquids have a somewhat higher absorption than lens materials. For that reason the maximum geometrical path lengths
20 within the immersion liquid should be kept small. Finally, a small curvature simplifies the access to the image side surface of the last optical element for cleaning purposes.

Therefore it is generally preferred if the immersion liquid
25 forms a convexly curved interface with a medium adjoining the immersion liquid towards the object plane such that light rays pass the interface with a maximum

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angle of incidence whose sine is between 0.98 and 0.5, more preferably between 0.95 and 0.85, and even more preferably between 0.94 and 0.87. The latter values correspond to angles of incidence of 60° and 70°, respectively. The angle of incidence here denotes the angle between the light ray and a surface normal at the point where the light ray impinges on the surface. These configurations are also advantageous if the refractive index of the immersion liquid is equal to, or smaller than the refractive index of the medium that adjoins the immersion liquid on the object side.

The very high numerical apertures possible according to the invention, which may be, for example, 1.6 and above, require, under some circumstances, a novel design of the projection objective. In this connection, a catadioptric projection objective comprising at least two imaging mirrors in which at least two intermediate images may be advantageous. Such a configuration is also advantageous if the refractive index of the immersion liquid is equal to or smaller than the refractive index of the medium that adjoins the immersion liquid on the object side.

BRIEF DESCRIPTION OF THE DRAWINGS

Various features and advantages of the present invention may be more readily understood with reference to the following detailed description taken in conjunction with the
5 accompanying drawing in which:

Figure 1 shows a meridian section through a microlithographic projection exposure apparatus having a projection objective according to the invention in a considerably simplified view that is not
10 to scale;

Figure 2 shows an enlarged view of the image-side end of the projection objective shown in Figure 1;

Figure 3 shows an enlarged view similar to Figure 2 for an alternative embodiment with a drainage barrier;
15

Figure 4 shows the image-side end of a projection objective in accordance with another exemplary embodiment in which an intermediate liquid has been introduced between the immersion liquid
20 and the last optical element on the image side;

Figure 5 shows details of the geometrical conditions at the image-side end of a projection objective according to the invention;

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Figure 6 shows a meridian section through a catadioptric projection objective in accordance with an embodiment the present invention;

5 Figure 7 shows a meridian section through a catadioptric projection objective in accordance with a further embodiment the present invention;

Figure 8 shows a meridian section through a catadioptric projection objective in accordance with another embodiment the present invention;

10 Figure 9 shows a meridian section through a complete catadioptric projection objective in accordance with still another embodiment the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

15 Figure 1 shows a meridian section through a microlithographic projection exposure apparatus denoted in its entirety by 110 in a considerably simplified view that is not to scale. The projection exposure apparatus 110 comprises an illuminating system 112 for generating projection light 113 including a light source 114, illumination
20 optics indicated by 116 and a diaphragm 118. In the exemplary embodiment shown, the projection light 113 has a wavelength of 193 nm.

The projection exposure apparatus 110 furthermore includes a projection objective 120 that comprises a multiplicity of lens elements, of which, for the sake of clarity, only a few are indicated by way of example in Figure 1 and are denoted by L1 to L5. The projection objective 120 images a mask 124 disposed in an object plane 122 of the projection objective 120 on a reduced scale on a photosensitive layer 126. The layer 126, which may be composed of a photoresist, is disposed in an image plane 128 of the projection objective 120 and is applied to a substrate 130. The photosensitive layer 126 may itself be composed of a plurality of layers and may also comprise antireflection layers, as is known in the art as such.

An immersion liquid 134 has been introduced into a gap 132 that remains between the last lens element L5 on the image side and the photosensitive layer 126.

This can be seen more clearly in Figure 2 that shows the image-side end of the projection objective 120 on an enlarged scale. The last lens element L5 on the image side has, on the image side, a surface 136 that is concavely curved. The gap 132 between the last lens element L5 on the image side and the photosensitive layer 126, which is usually flat at both ends, now transforms into a kind of cavity.

The surface 136 is approximately of spherical shell shape, the radius of curvature being denoted in Figure 2

by R. In this arrangement, the radius of curvature R is about 1.3 times the axial distance s between the last lens element L5 on the image side and the photosensitive layer 126.

5 The immersion liquid 134 has a refractive index n_L that is greater than the refractive index of the material n_1 of which the last lens element L5 on the image side is composed. If, for example, quartz glass or calcium fluoride is used as material, a liquid should be chosen whose
10 refractive index n_L is above 1.56 or 1.5. This can be achieved, for example, by adding sulphates, alkalis such as caesium, or phosphates to water, as is described on Internet page www.eetimes.com/semi/news/OEG20040128S0017. These immersion liquids have sufficient transparency and
15 stability even at wavelengths in the deep ultraviolet spectral range. If the projection exposure apparatus 110 is designed for longer wavelengths, for example for wavelengths in the visible spectral range, conventional immersion liquids having high refractive index, such as,
20 for example, cedarwood oil, carbon disulphide or monobromonaphthalene may also be used as immersion liquid.

Since the immersion liquid forms, with respect to the object plane 122, a convexly curved interface 139 with the last lens element L5 on the image side, only relatively
25 small beam incidence angles occur at said interface 139. This is shown in Figure 2 by way of example for aperture rays 113a and 113b having a maximum aperture angles α . As

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a result, reflection losses at said interface are correspondingly small. Thus rays having large aperture angles with respect to an optical axis OA of the projection objective 120 may also contribute to forming an image of
5 the mask 124, with the result that it is possible to achieve with the projection objective 120 numerical apertures that extend up to the refractive index n_L of the immersion liquid 134. If, on the other hand, the interface 139 were plane, as is usual in the prior art, said
10 rays would be totally reflected at the interface between the last lens element L5 and the immersion liquid.

Figure 3 shows a projection objective 120 in accordance with another exemplary embodiment in a view along the lines of Figure 2. Identical parts are characterized in
15 the figure by identical reference numerals.

The projection objective 120' differs from the projection objective 120 shown in Figures 1 and 2 only in that a ring 140 is tightly joined to the last lens element L5 and a housing 141 of the projection objective 120. The
20 ring 140 functions as a drainage barrier for the immersion liquid 134. Such a drainage barrier may be particularly advantageous if the surface 136 of the last lens element L5 on the image side is strongly curved since then the gap 132 has a large maximum extension along the
25 optical axis OA. Accordingly, the hydrostatic pressure of the immersion liquid 134 is relatively high. Without a drainage barrier, said pressure may ultimately have the

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result that the immersion liquid 134 is forced out of the cavity into the surrounding gap 132 between the projection objective 120 and the photosensitive layer 126 so that a surrounding gas may enter the cavity.

5 The ring 140 may be composed, for example, of a standard lens material such as quartz glass or calcium chloride, but also of other materials, such as InvarTM nickel alloy, stainless steel or (glass) ceramic.

10 Figure 4 shows an image-side end of a projection objective 120" in accordance with a further exemplary embodiment in which a curvature of the immersion liquid 134 is achieved in another way.

In the projection objective 120", the immersion liquid 134 does not directly adjoin a last lens element L5" on the image side. Instead, a further liquid, which is referred to in the following as intermediate liquid 142, is situated between the last lens element L5" on the image side and the immersion liquid 134. The intermediate liquid 142 is, in the embodiment shown, water to which ions have been added. Due to the ions the water becomes electrically conductive. The immersion liquid 134, which also in this case has a greater refractive index than the last lens element L5", is electrically insulating. For wavelengths of the projection light that are in the visible spectral range, the oils and naphthalenes already men-

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tioned above are, for example, suitable as immersion liquid 134.

The intermediate liquid 142 completely fills the space that remains between an image-side surface 136" of the last lens element L5" on the image side and the immersion liquid 134. The surface 136" is convexly curved in the exemplary embodiment shown, but the latter may also be a plane surface. Adjacent to a ring 140" that, as in the exemplary embodiment described above, has the function of a drainage barrier, a likewise annular conical electrode 146 is provided that is connected to a controllable voltage source 147. Applied to the conical electrode 146 is an insulator layer 148 that, together with the photosensitive layer 126, ensures continuous insulation of the immersion liquid 134 with respect to the image plane. The voltage source 147 generates an alternating voltage whose frequency is between 100 kHz and 500 kHz. The voltage applied to the conical electrode 146 is in the order of magnitude of about 40 V.

When the alternating voltage is applied to the conical electrode 146, the electrowetting effect known as such has the result that the interface 139 between the immersion liquid 134 and the intermediate liquid 142 convexly curves towards the object plane 122. The cause of this curvature is capillary forces that, together with the unalterability of the total volume and the tendency to the formation of a minimum surface, generate, to a good

approximation, a spherical interface 139 if a sufficiently high alternating voltage is applied to electrode 146.

If the alternating voltage is now reduced, the curvature of the interface 139 decreases. In Figure 4 this is indicated by an interface 139' shown as a broken line. The refractive index of the liquid lens formed by the immersion liquid 134 can consequently be continuously varied in a simple way, namely by altering the electrical alternating voltage applied to the conical electrode 146. For the sake of completeness, it may also be mentioned at this point that the curvature of the interface 139 does not necessarily require an alternating voltage, but may also be achieved with a direct voltage.

Also in this embodiment, the interface of the immersion liquid 134 that is convexly curved towards the object plane 122 has the effect that a numerical aperture can be achieved that is limited not by the refractive index of the last lens element L5" but only by the refractive index of the immersion liquid 134.

The continuous variability of the refractive power of the liquid lens formed by the immersion liquid 134 can advantageously also be used at other locations in the projection objective. Advantageously, such a liquid lens can be used at positions inside the projection objective that are exposed to particularly high light intensities. Degradation phenomena, such as occur in the case of conven-

tional solid lenses, can be suppressed in this way or at least be repaired by simply replacing the immersion liquid. Incidentally, corresponding remarks also apply to the embodiments shown in Figures 2 and 3.

5 Figure 5 shows an image-side end of a projection objective according to a still further exemplary embodiment. Here the last lens element L205 has a spherical surface 236 facing towards the image plane that has a smaller concave curvature, i.e. a larger radius R, than the lens
10 element L5 in the embodiments shown in Figures 2 and 3. In the following the geometrical conditions at the interface between the last lens element L205 and the immersion liquid 134 will be discussed in further detail.

Reference numeral AR denotes an aperture ray having a
15 maximum aperture angle ϕ . The aperture ray AR impinges on the photosensitive layer 126 at a peripheral point of the image field at a height h with respect to the optical axis OA. The aperture ray AR has an angle of incidence α and an angle of refraction β at the interface between the
20 last lens element L205 and the immersion liquid 134. The distance between the vertex of the last surface 236 of the lens element L205 and the image plane in which the photosensitive layer 126 is positioned is denoted by s.

Projection objectives are basically characterized by two
25 quantities, namely the image-side numerical aperture

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$$NA = n \cdot \sin(\varphi)$$

and the quantity $2h$, i.e. the diameter of a circle around the optical axis OA on which an image can be formed.

From the image-side numerical aperture NA certain geomet-
5 rical properties can be derived which ensure that the
light can propagate through the last lens element and im-
mersion liquid without being reflected at the interfaces.
However, the design requirements applied to the last lens
element are, in practice, somewhat stricter than those
10 that can be derived solely from the image-side numerical
aperture. For example, the angle of incidence α should
not exceed a certain value that is, for example, about
75°, and more preferably 70°. This is because experience
shows that projection objectives having larger angles of
15 incidence α require very complex measures to achieve a
good aberration correction and a reduced sensitivity to
manufacturing tolerances and changing environmental con-
ditions.

At present projection objectives for dry operation
20 achieve an image-side NA close to about 0.95. This means
that the numerical aperture NA does not exceed 95% of the
refractive index of the medium (usually a gas or a mix-
ture of gases such as air) that immediately precedes the
image plane. In such dry projection objectives the maxi-
25 mum angles of incidence are in the order of about 70°, in

particular at the last surfaces close to the image plane but also at other surfaces of lens elements..

Since these considerations also apply to immersion objectives, the angles of incidence should be kept below these values. From geometrical considerations it becomes clear
5 that the stronger the curvature of the surface 236 is, the smaller are the angles of incidence. Thus a strong curvature ensures that the angles of incidence do not go beyond these values.

10 The surface 236 of the lens element L205 should, on the other hand, not be too severely curved. This is due to the fact that a too severely curvature may result in increased problems with respect to flow mechanics, contamination and temperature sensitivity of the immersion liquid 134. For example, it may be difficult to achieve a
15 homogenous and constant temperature of the immersion liquid 134, and the immersion liquid 134 may be enclosed in such a way within a strongly convex cavity that replacing the immersion liquid, for example for purging reasons,
20 becomes a very complex task.

It has been found out that a good compromise is achieved if the following condition holds for the maximum angle of incidence α :

$$0.95 > \sin(\alpha) > 0.85.$$

In the following a formula is derived that specifies a suitable curvature ρ as a function of $NA = n \cdot \sin(\varphi)$, distance s , image height h and the refractive indices n' , n of the last lens element L205 and the immersion liquid 134, respectively, so that the sine of the angle of incidence α does not exceed a certain advantageous and practicable value. Such a value was found to be $\sin(\alpha) < \kappa$, where $\kappa = 0.95$. Using the law of refraction, it follows that

$$10 \quad \left| \frac{n}{n'} \sin(\beta) \right| > \kappa$$

According to simple geometrical considerations, it can be deduced therefrom that

$$\left| \frac{n}{n'} (s\rho - 1) \sin(\varphi) \right| > \kappa$$

Thus

$$15 \quad \rho > \frac{\left(1 - \frac{n' \cdot \kappa}{NA}\right)}{s}$$

is the condition for minimum surface curvature. For the radius $R = 1/\rho$ this gives

$$R > \frac{s}{\left(1 - \frac{n' \cdot \kappa}{NA}\right)}$$

For an exemplary numerical aperture $NA = 1.5$ and SiO_2 as material for the last lens element L205 with $n' = 1.56$, this results in

5 $R > m \cdot s$

with $m \approx 83$. For $s = 2$ mm, this leads to a radius R of about 167 mm for the maximum radius of curvature.

If, in addition, the aperture rays of the outermost image point are taken into account in the case of a finite image field, it is sufficient for this purpose to substitute the distance s by s' according to

10

$$s' = s \frac{h}{\tan \varphi}$$

in the above formulae. For a maximum field height h , it then follows for the minimum curvature ρ

15 $\rho > \left(1 - \frac{n' \cdot \kappa}{NA}\right) / \left(s - \frac{h}{\tan \varphi}\right)$

If one starts with a projection objective having the above mentioned parameters, i.e. $NA = 1.5$ and $n' = 1.56$,

and if one further assumes that the maximum field height h is 15 mm, the maximum radius of curvature R should be below $m = 83$ times ($s = 5.57$ mm). For $s = 8$ mm, this results in a maximum radius of curvature R of approximately
5 200 mm, and for $s = 10$ mm R is approximately 375 mm.

If, for example, κ is selected to be 0.95 and an immersion liquid with a refractive index of $n = 1.43$ is used, a numerical aperture $NA = 1.35$ may be realized with a last lens element L205 that is made of SiO_2 and which has
10 a distance $s = 2$ mm to the image plane and has a maximum radius of curvature below approximately 80 mm. The aforementioned detrimental effects that occur in the case of large curvatures can be minimized if the maximum radius of the surface is not only below the given values, but at
15 least substantially identical to these values.

Apart from the fact that the maximum angle of incidence should not exceed certain upper and lower limits as is explained above, it should be ensured that the light rays rather quickly converge if one looks from a point on the
20 image plane towards the object plane. Otherwise optical elements with very large diameters would be required. This qualitative design rule can be mathematically expressed in the following way: If k , l , m are the three direction cosines of an aperture ray and n is the refractive
25 tive within a medium with $k^2 + l^2 + m^2 = n^2$, there should be no volume in the objective (particularly in the vicinity of the image plane) in which $(k^2 + l^2)/n^2 > K_0$. The

limit K_0 may be selected to be $K_0 = 0.95$ or even better $K_0 = 0.85$.

Figure 6 shows a meridian section through a first exemplary embodiment of the projection objective 120 shown in Figures 1 and 2. The design data of the projection objective are listed in Table 1; radii and thicknesses are specified in millimeters. The numerals above the projection objective point to selected surfaces of optical elements. Surfaces that are characterized by groups of short bars are aspherically curved. The curvature of said surfaces is described by the aspherical formula below:

$$z = \frac{ch^2}{1 + \sqrt{1 - (1 + k) c^2 h^2}} + Ah^4 + Bh^6 + Ch^8 + Dh^{10} + Eh^{12} + Fh^{14}$$

In this equation, z is the saggita of the respective surface parallel to the optical axis, h is the radial distance from the optical axis, $c = 1/R$ is the curvature at the vertex of the respective surface where R is the radius of curvature, k is the conical constant and A , B , C , D , E and F are the aspherical constants listed in Table 2. In the exemplary embodiment, the spherical constant k equals zero.

The projection objective 120 contains two aspherical mirrors S1 and S2 between which two (not optimally corrected) intermediate images are produced. The projection

objective 120 is designed for a wavelength of 193 nm and a refractive index n_L of the immersion liquid of 1.60. The linear magnification of the projection objective 120 is $\beta = -0.25$ and the numerical aperture is $NA = 1.4$. Some
5 additional improvements, however, make it possible to achieve without difficulty also a numerical aperture NA that just reaches the refractive index of the immersion medium and is, consequently, only slightly less than 1.6.

Figures 7 to 9 show meridian sections through three further exemplary embodiments of the projection objective
10 120 shown in Figures 1 and 2. The design data and aspherical constants of the projection objective shown in Figure 7 are listed in Tables 3 and 4; Tables 5, 6 and Tables 7, 8 list the design data and aspherical constants
15 for the embodiments shown in Figure 8 and 9, respectively.

The projection objectives shown in Figures 7 to 9 all have an image-side numerical aperture $NA = 1.40$ and an immersion liquid with a refractive index of $n_L = 1.60$.
20 Thus this refractive index is always greater than the refractive index of the last lens element made of CaF_2 , i.e. $n_L > n_{\text{CaF}_2}$.

The projection objective shown in Figure 7, which is designed for a wavelength $\lambda = 193$ nm, is non-achromatized
25 and has a last lens element LL7 with a strongly concavely curved image-side surface that forms a kind of cavity for

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the immersion liquid 134. The wavefront is corrected to about $2/100 \lambda$.

The projection objective shown in Figure 8 is designed for a wavelength $\lambda = 157 \text{ nm}$ and is achromatized. The image-side surface of the last lens element LL8 is even stronger concavely curved; apart from that, the radius of curvature is almost identical with the axial distance between the last lens element LL8 and the image plane, i.e. the center of curvature lies substantially within the image plane. As a result, the immersion liquid 134 has a large maximum thickness. Although the refractive index of CaF_2 is about $n_{\text{CaF}_2} = 1.56$ at $\lambda = 157 \text{ nm}$, the refractive index of the immersion liquid is still assumed to be larger ($n_L = 1.60$). The wavefront is corrected to about $4/100 \lambda$.

The projection objective shown in Figure 9 is designed for a wavelength $\lambda = 193 \text{ nm}$ and is non-achromatized. The image-side surface of the last lens element LL9 has only a small concave curvature so that the immersion liquid 934 forms almost a flat layer. The radius of curvature is significantly (about a factor 10) greater than the axial distance between the last lens element LL9 and the image plane, i.e. there is a substantial distance between the center of curvature and the image plane. The maximum angle of incidence at the interface between the last lens element LL9 and the immersion liquid 934 is about 67° .

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(i.e. $\sin \alpha = 0.92$). The wavefront is corrected to about $5/100 \lambda$.

When comparing the wavefront errors in the similar embodiments shown in Figures 7 and 9, it becomes clear that the design of Figure 7 with its greater curvature of the image-side surface of the last lens element LL7 allows to achieve a much better wavefront correction ($2/100 \lambda$ vs. $5/100 \lambda$). However, although the projection objective shown in Figure 9 is not as well corrected as the projection objective shown in Figure 7, due to the comparatively large radius of curvature there is only a small cavity underneath the last lens element LL9 which is advantageous for the reasons that have been mentioned above.

It goes without saying that the present invention is not restricted to the use in catadioptric projection objectives as have been described above. The invention can also advantageously be used in projection objectives having a smaller or larger number of intermediate images than in the embodiments shown, and also in dioptric projection objectives with or without any intermediate images. In addition, the optical axis may also extend through the center of the image field. Examples of further suitable lens designs are to be found, for example, in US 2002/0196533 A1, WO 01/050171 A1, WO 02/093209 A2 and US 6496306 A.

Table 1: Design data

| SURFACE | RADIUS | ASPHERICAL | THICKNESS | MATERIAL |
|--------------|-----------|------------|-----------|------------------|
| Object plane | ∞ | | 37,648 | |
| 1 | 210,931 | | 21,995 | SiO ₂ |
| 2 | 909,02 | | 1,605 | |
| 3 | 673,572 | | 22,728 | SiO ₂ |
| 4 | -338,735 | x | 33,19 | |
| 5 | 130,215 | x | 8,994 | SiO ₂ |
| 6 | 119,808 | | 36,001 | |
| 7 | 216 | | 40,356 | SiO ₂ |
| 8 | -210,59 | | 0,939 | |
| 9 | 97,24 | | 49,504 | SiO ₂ |
| 10 | 216,208 | x | 8,164 | |
| 12 | -65,704 | | 49,734 | SiO ₂ |
| Diaphragm | ∞ | | 49,302 | |
| 13 | -113,325 | | 55,26 | |
| 14 | -6210,149 | x | 70,31 | SiO ₂ |
| 15 | -195,536 | | 0,962 | |
| 16 | 3980,16 | | 65,997 | SiO ₂ |
| 17 | -473,059 | | 277,072 | |
| 18 | -225,942 | x | 246,731 | Mirror |
| 19 | 193,745 | x | 294,329 | Mirror |
| 20 | -338,56 | x | 17,389 | SiO ₂ |
| 21 | -206,244 | | 8,884 | |
| 22 | -148,97 | | 34,064 | SiO ₂ |
| 23 | 129,921 | x | 40,529 | |
| 24 | -2704,885 | | 33,192 | SiO ₂ |
| 25 | -195,599 | | 0,946 | |
| 26 | -794,214 | x | 30,169 | SiO ₂ |
| 27 | -479,39 | | 24,236 | |
| 28 | -311,778 | x | 100,056 | SiO ₂ |
| 29 | -159,333 | | 28,806 | |
| 30 | 309,839 | | 43,609 | SiO ₂ |
| 31 | 836,077 | x | 0,951 | |
| 32 | 225,096 | | 55,667 | SiO ₂ |
| 33 | 687,556 | | 0,945 | |
| 34 | 154,575 | | 64,278 | SiO ₂ |
| 35 | 911,8 | x | 0,932 | |
| 36 | 89,986 | | 44,143 | SiO ₂ |
| 37 | 199,475 | x | 0,878 | |
| 38 | 61,984 | | 9,635 | SiO ₂ |
| 39 | 35,475 | | 34,43 | Liquid |
| 40 | ∞ | | | Resist |

Table 2: Aspherical constants

| | | | | | |
|------------|-----------------|------------|-----------------|------------|-----------------|
| Surface 4 | | Surface 5 | | Surface 10 | |
| A | 5,36225288E-08 | A | 2,53854010E-08 | A | 4,51137087E-07 |
| B | -5,17992581E-12 | B | -1,22713179E-11 | B | 2,46833840E-11 |
| C | 8,49599769E-16 | C | 1,21417341E-15 | C | 5,78496960E-15 |
| D | -7,57832730E-20 | D | -1,92474180E-19 | D | -4,39101683E-18 |
| E | 3,59228710E-24 | E | 2,08240691E-23 | E | -5,64853356E-22 |
| F | -9,16722201E-29 | F | -9,29539601E-28 | F | 4,95744749E-26 |
| Surface 14 | | Surface 18 | | Surface 19 | |
| A | -8,48905023E-09 | A | 1,04673033E-08 | A | -4,11099367E-09 |
| B | 1,45061822E-13 | B | 1,34351117E-13 | B | -9,91828838E-14 |
| C | -6,34351367E-18 | C | 1,03389626E-18 | C | -7,93614779E-19 |
| D | 2,84301572E-22 | D | 5,16847878E-23 | D | -1,66363646E-22 |
| E | -8,24902650E-27 | E | -1,23928686E-27 | E | 5,56486530E-27 |
| F | 1,27798308E-31 | F | 3,09904827E-32 | F | -1,79683490E-31 |
| Surface 20 | | Surface 23 | | Surface 26 | |
| A | 1,14749646E-07 | A | -2,87603531E-08 | A | -4,35420789E-08 |
| B | -8,19248307E-12 | B | -9,68432739E-12 | B | -6,70429494E-13 |
| C | 8,78420843E-16 | C | 6,88099059E-16 | C | -4,05835225E-17 |
| D | -1,39638210E-19 | D | -8,70009838E-20 | D | -1,10658303E-20 |
| E | 2,09064504E-23 | E | 9,59884320E-24 | E | 4,80978147E-25 |
| F | -2,15981914E-27 | F | -5,07639229E-28 | F | -5,35014389E-29 |
| Surface 28 | | Surface 31 | | Surface 35 | |
| A | -2,70754285E-08 | A | 4,38707762E-09 | A | 1,73743303E-08 |
| B | -1,36708653E-12 | B | -3,69893805E-13 | B | 1,60994523E-12 |
| C | -2,46085956E-17 | C | -4,93747026E-18 | C | -1,71036162E-16 |
| D | 2,26651081E-21 | D | 4,05461849E-22 | D | 1,26964535E-20 |
| E | -1,20009586E-25 | E | -7,59674606E-27 | E | -5,77497378E-25 |
| F | 9,28622501E-30 | F | 5,58403314E-32 | F | 1,55390733E-29 |
| Surface 37 | | | | G | -1,78430224E-34 |
| A | 1,04975421E-07 | | | | |
| B | 1,94141448E-11 | | | | |
| C | -2,31145732E-15 | | | | |
| D | 4,57201996E-19 | | | | |
| E | -3,92356845E-23 | | | | |
| F | 2,35233647E-27 | | | | |

Table 3: Design data

| SURFACE | RADIUS | THICKNESS | MATERIAL | INDEX | SEMI DIAM |
|---------|------------|-----------|------------------|----------|-----------|
| 0 | ∞ | 32.0000 | | | 65.50 |
| 1 | ∞ | 0.0000 | | | 80.45 |
| 2 | 332.4480 | 18.9959 | SiO ₂ | 1.560318 | 84.22 |
| 3 | 27083.8930 | 17.5539 | | | 85.42 |
| 4 | -253.5666 | 26.7129 | SiO ₂ | 1.560318 | 86.06 |
| 5 | -179.3607 | 164.1318 | | | 90.72 |
| 6 | 1920.0084 | 34.5089 | SiO ₂ | 1.560318 | 111.13 |
| 7 | -279.4103 | 0.9461 | | | 111.59 |
| 8 | 213.6767 | 34.3917 | SiO ₂ | 1.560318 | 103.48 |
| 9 | 17137.3629 | 26.7484 | | | 100.67 |
| 10 | -208.9766 | 9.4997 | SiO ₂ | 1.560318 | 99.22 |
| 11 | -609.1513 | 0.9500 | | | 97.67 |
| 12 | 734.0560 | 18.8742 | SiO ₂ | 1.560318 | 95.00 |
| 13 | -1380.9253 | 24.2008 | | | 93.32 |
| 14 | ∞ | 231.0887 | | | 81.98 |
| 15 | 252.7510 | 74.6720 | SiO ₂ | 1.560318 | 126.43 |
| 16 | 1098.5274 | 0.9492 | | | 121.38 |
| 17 | 268.9906 | 50.1845 | SiO ₂ | 1.560318 | 119.28 |
| 18 | -463.5300 | 1.0915 | | | 117.08 |
| 19 | 697.8278 | 30.0054 | SiO ₂ | 1.560318 | 106.59 |
| 20 | 292.0140 | 120.0163 | | | 94.90 |
| 21 | ∞ | 9.9914 | | | 82.23 |
| 22 | ∞ | -100.0083 | Mirror | 1.560318 | 142.10 |
| 23 | -178.0803 | -45.0048 | SiO ₂ | 1.560318 | 115.52 |
| 24 | -663.9291 | -95.3149 | | | 113.38 |
| 25 | -237.9404 | -15.0000 | SiO ₂ | 1.560318 | 115.72 |
| 26 | -166.3412 | -152.4364 | | | 111.11 |
| 27 | 222.8026 | -15.0000 | SiO ₂ | 1.560318 | 127.22 |
| 28 | 539.8416 | -94.3687 | | | 138.91 |
| 29 | 364.8709 | 94.3687 | Mirror | | 167.04 |
| 30 | 539.8416 | 15.0000 | SiO ₂ | 1.560318 | 138.91 |
| 31 | 222.8026 | 152.4364 | | | 127.22 |
| 32 | -166.3412 | 15.0000 | SiO ₂ | 1.560318 | 111.11 |
| 33 | -237.9404 | 95.3149 | | | 115.72 |
| 34 | -663.9291 | 45.0048 | SiO ₂ | 1.560318 | 113.38 |
| 35 | -178.0803 | 100.0083 | | | 115.52 |
| 36 | ∞ | 94.5942 | | | 122.31 |
| 37 | ∞ | -23.8903 | | | 91.10 |
| 38 | ∞ | 20.0000 | | | 179.89 |
| 39 | 254.8239 | 29.5175 | SiO ₂ | 1.560318 | 96.82 |
| 40 | -2985.0549 | 36.7407 | | | 96.62 |
| 41 | 200.4128 | 45.9683 | SiO ₂ | 1.560318 | 106.20 |
| 42 | -666.1976 | 170.5500 | | | 105.01 |

| | | | | | |
|----|------------|-----------|------------------|----------|--------|
| 43 | -95.1516 | 15.0000 | SiO ₂ | 1.560318 | 77.96 |
| 44 | -643.9252 | 55.6492 | | | 95.09 |
| 45 | -175.8508 | -55.6492 | Mirror | | 109.51 |
| 46 | -643.9252 | -15.0000 | SiO ₂ | 1.560318 | 95.09 |
| 47 | -95.1516 | -170.5500 | | | 77.96 |
| 48 | -666.1976 | -45.9683 | SiO ₂ | 1.560318 | 105.01 |
| 49 | 200.4128 | -12.1735 | | | 106.20 |
| 50 | ∞ | -24.5646 | | | 90.83 |
| 51 | -2985.0549 | -29.5175 | SiO ₂ | 1.560318 | 96.62 |
| 52 | 254.8239 | -20.0000 | | | 96.82 |
| 53 | ∞ | 180.1673 | Mirror | | 134.73 |
| 54 | -148.5117 | 25.7491 | SiO ₂ | 1.560318 | 95.86 |
| 55 | 327.9861 | 43.1843 | | | 116.84 |
| 56 | -496.1113 | 30.0070 | SiO ₂ | 1.560318 | 124.28 |
| 57 | -252.6773 | 19.1777 | | | 130.89 |
| 58 | 1365.3904 | 68.1411 | SiO ₂ | 1.560318 | 165.17 |
| 59 | -284.3746 | 73.5313 | | | 172.58 |
| 60 | 754.4880 | 93.5313 | SiO ₂ | 1.560318 | 234.19 |
| 61 | -588.1067 | 54.2510 | | | 235.10 |
| 62 | 357.9132 | 85.3268 | SiO ₂ | 1.560318 | 221.99 |
| 63 | -762.8649 | 0.9929 | | | 220.72 |
| 64 | 304.8598 | 57.6484 | SiO ₂ | 1.560318 | 181.91 |
| 65 | 1098.9629 | 0.9340 | | | 177.48 |
| 66 | 143.0811 | 62.6047 | SiO ₂ | 1.560318 | 127.33 |
| 67 | 347.6273 | 0.9010 | | | 177.47 |
| 68 | 79.6669 | 50.1800 | CaF ₂ | 1.501403 | 73.25 |
| 69 | 36.1540 | 21.2194 | Liquid | 1.600000 | 31.82 |
| 70 | ∞ | | | | 19.38 |

Table 4: Aspherical constants

| SURFACE | 3 | 19 | 24 | 28 | 30 |
|---------|---------------|---------------|---------------|---------------|---------------|
| K | 0 | 0 | 0 | 0 | 0 |
| A | 4.047232E-09 | -4.175853E-08 | -3.889430E-08 | 6.661869E-09 | 6.661869E-09 |
| B | 8.449241E-13 | -5.621416E-13 | 2.260825E-13 | 2.899240E-13 | 2.899240E-13 |
| C | 5.603175E-17 | -2.909466E-19 | 9.880822E-18 | -1.932302E-17 | -1.932302E-17 |
| D | -4.004583E-21 | 3.690043E-22 | -2.672567E-22 | 1.602360E-21 | 1.602360E-21 |
| E | -8.168767E-25 | 2.119217E-26 | 4.717688E-26 | -6.342246E-26 | -6.342246E-26 |
| F | 2.123279E-29 | -9.535588E-31 | -3.817055E-30 | 1.183564E-30 | 1.183564E-30 |
| SURFACE | 34 | 39 | 44 | 46 | 52 |
| K | 0 | 0 | 0 | 0 | 0 |
| A | -3.889430E-08 | -2.037803E-08 | -1.157857E-08 | -1.157857E-08 | -2.037803E-08 |
| B | 2.260825E-13 | -6.612137E-13 | 1.455623E-12 | 1.455623E-12 | -6.612137E-13 |
| C | 9.880822E-18 | 2.840028E-17 | -5.746524E-17 | -5.746524E-17 | 2.840028E-17 |
| D | -2.672567E-22 | -4.931922E-21 | 1.261354E-21 | 1.261354E-21 | -4.931922E-21 |
| E | 4.717688E-26 | 4.142905E-25 | 4.054615E-25 | 4.054615E-25 | 4.142905E-25 |
| F | -3.817055E-30 | -1.562251E-29 | -2.761361E-29 | -2.761361E-29 | -1.562251E-29 |
| SURFACE | 58 | 62 | 65 | 67 | |
| K | 0 | 0 | 0 | 0 | |
| A | -1.679180E-08 | -1.483428E-08 | -9.489171E-09 | -1.782977E-08 | |
| B | -5.846864E-14 | -2.269457E-14 | 5.001612E-13 | 9.574096E-13 | |
| C | 7.385649E-18 | 4.944523E-18 | -1.283531E-17 | 7.878477E-17 | |
| D | -5.142028E-22 | -1.410026E-22 | -8.674473E-23 | -7.167182E-21 | |
| E | 1.479187E-26 | 1.643655E-27 | 7.103644E-27 | 2.682224E-25 | |
| F | -2.189903E-31 | -7.668842E-33 | -7.251904E-32 | -3.423260E-30 | |

Table 5: Design data

| SURFACE | RADIUS | THICKNESS | MATERIAL | INDEX | SEMI DIAM |
|---------|------------|-----------|------------------|----------|-----------|
| 0 | ∞ | 32.0000 | | | 65.50 |
| 1 | ∞ | 0.0000 | | | 80.46 |
| 2 | 3568.5495 | 29.3610 | CAF ₂ | 1.555560 | 80.77 |
| 3 | -306.4778 | 50.8080 | | | 84.99 |
| 4 | -495.7015 | 32.5298 | CAF ₂ | 1.555560 | 97.37 |
| 5 | -161.1181 | 81.4155 | | | 99.50 |
| 6 | 188.0753 | 36.2525 | CAF ₂ | 1.555560 | 93.00 |
| 7 | -1013.7352 | 6.1886 | | | 90.93 |
| 8 | 288.3482 | 26.9703 | CAF ₂ | 1.555560 | 82.17 |
| 9 | 872.7887 | 32.5801 | | | 74.60 |
| 10 | ∞ | 47.8395 | | | 57.76 |
| 11 | -76.3176 | 12.9591 | CAF ₂ | 1.555560 | 65.40 |
| 12 | -82.8195 | 72.8834 | | | 71.21 |
| 13 | 494.0581 | 30.0025 | CAF ₂ | 1.555560 | 105.98 |
| 14 | 500.2689 | 0.9499 | | | 109.01 |
| 15 | 210.1705 | 55.9335 | CAF ₂ | 1.555560 | 115.54 |
| 16 | -462.2471 | 0.9442 | | | 114.96 |
| 17 | 191.5029 | 28.1484 | CAF ₂ | 1.555560 | 104.19 |
| 18 | 469.5739 | 3.8083 | | | 100.65 |
| 19 | 313.4359 | 9.4935 | CAF ₂ | 1.555560 | 99.24 |
| 20 | 161.6230 | 115.1964 | | | 91.07 |
| 21 | ∞ | 14.7967 | | | 90.40 |
| 22 | ∞ | -100.0183 | Mirror | | 206.37 |
| 23 | -247.2670 | -56.5211 | CAF ₂ | 1.555560 | 148.25 |
| 24 | 1546.1350 | -403.3917 | | | 147.84 |
| 25 | 500.0000 | -25.0000 | CAF ₂ | 1.555560 | 142.88 |
| 26 | -2059.5717 | -87.3199 | | | 147.68 |
| 27 | 173.4701 | -25.0000 | CAF ₂ | 1.555560 | 148.30 |
| 28 | 823.5657 | -65.7941 | | | 193.66 |
| 29 | 295.8639 | 65.7941 | Mirror | | 204.70 |
| 30 | 823.5657 | 25.0000 | CAF ₂ | 1.555560 | 193.66 |
| 31 | 173.4701 | 87.3199 | | | 148.30 |
| 32 | -2059.5717 | 25.0000 | CAF ₂ | 1.555560 | 147.68 |
| 33 | 500.0000 | 403.3917 | | | 142.88 |
| 34 | 1546.1350 | 56.5211 | CAF ₂ | 1.555560 | 147.84 |
| 35 | -247.2670 | 100.0183 | | | 148.25 |
| 36 | ∞ | 49.8789 | | | 125.86 |
| 37 | ∞ | 20.8278 | | | 89.12 |
| 38 | ∞ | 20.0000 | | | 149.02 |
| 39 | 215.5222 | 38.8898 | CAF ₂ | 1.555560 | 91.59 |
| 40 | -548.9606 | 360.6137 | | | 90.02 |
| 41 | -126.6780 | 15.0000 | CAF ₂ | 1.555560 | 120.92 |
| 42 | -567.9480 | 48.8335 | | | 169.01 |
| 43 | -224.2817 | -48.8335 | Mirror | | 171.87 |

| | | | | | |
|----|------------|-----------|------------------|----------|--------|
| 44 | -567.9480 | -15.0000 | CAF ₂ | 1.555560 | 169.01 |
| 45 | -126.6780 | -314.8668 | | | 120.92 |
| 46 | ∞ | -45.7487 | | | 81.94 |
| 47 | -548.9606 | -38.8898 | CAF ₂ | 1.555560 | 90.02 |
| 48 | 215.5222 | -20.0000 | | | 91.59 |
| 49 | ∞ | 195.8787 | Mirror | | 133.74 |
| 50 | -121.2718 | 15.1499 | CAF ₂ | 1.555560 | 97.18 |
| 51 | 529.2614 | 24.3014 | | | 127.08 |
| 52 | -8438.5548 | 64.5537 | CAF ₂ | 1.555560 | 137.42 |
| 53 | -202.6253 | 25.2464 | | | 142.97 |
| 54 | -1447.9251 | 63.0634 | CAF ₂ | 1.555560 | 168.91 |
| 55 | -254.3816 | 80.5189 | | | 174.93 |
| 56 | 783.5550 | 57.0370 | CAF ₂ | 1.555560 | 203.06 |
| 57 | -939.7625 | 70.4486 | | | 203.12 |
| 58 | 358.1334 | 55.4484 | CAF ₂ | 1.555560 | 186.96 |
| 59 | 5861.2627 | 0.9614 | | | 184.33 |
| 60 | 259.9889 | 36.5173 | CAF ₂ | 1.555560 | 161.62 |
| 61 | 371.5128 | 0.8975 | | | 156.47 |
| 62 | 134.7936 | 77.4909 | CAF ₂ | 1.555560 | 127.53 |
| 63 | 767.8631 | 0.7967 | | | 119.07 |
| 64 | 72.9080 | 48.3195 | CAF ₂ | 1.555560 | 70.97 |
| 65 | 29.7284 | 27.0563 | IMMO16 | 1.600000 | 31.25 |
| 66 | ∞ | | | | 19.39 |

Table 6: Aspherical constants

| | | | | | |
|---------|---------------|---------------|---------------|---------------|---------------|
| SURFACE | 3 | 9 | 19 | 24 | 26 |
| K | 0 | 0 | 0 | 0 | 0 |
| A | 2.172737E-08 | 8.983641E-08 | -5.825972E-08 | -1.605889E-08 | -2.779244E-10 |
| B | 1.718631E-12 | -5.996759E-12 | -6.306762E-13 | 4.504977E-16 | -3.062909E-14 |
| C | 1.514127E-16 | 6.363808E-16 | -2.783920E-17 | 3.596627E-21 | 1.861506E-18 |
| D | -2.716770E-22 | -3.998733E-20 | -1.594705E-21 | 2.792862E-22 | -2.425072E-22 |
| E | -1.008203E-24 | -5.130142E-24 | 2.956685E-25 | -1.885291E-26 | 1.114443E-26 |
| F | -1.157181E-28 | 1.266998E-28 | -1.064251E-29 | 3.351694E-31 | -2.553147E-31 |
| SURFACE | 28 | 30 | 32 | 34 | 39 |
| K | 0 | 0 | 0 | 0 | 0 |
| A | 4.632690E-09 | 4.632690E-09 | -2.779244E-10 | -1.605889E-08 | -1.815667E-08 |
| B | -3.213384E-14 | -3.213384E-14 | -3.062909E-14 | 4.504977E-16 | -2.488991E-13 |
| C | 7.229632E-20 | 7.229632E-20 | 1.861506E-18 | 3.596627E-21 | 2.824306E-17 |
| D | 2.100335E-23 | 2.100335E-23 | -2.425072E-22 | 2.792862E-22 | -4.697303E-21 |
| E | -5.592560E-28 | -5.592560E-28 | 1.114443E-26 | -1.885291E-26 | 3.415362E-25 |
| F | 6.249291E-33 | 6.249291E-33 | -2.553147E-31 | 3.351694E-31 | -9.509214E-30 |
| SURFACE | 42 | 44 | 48 | 54 | 59 |
| K | 0 | 0 | 0 | 0 | 0 |
| A | -9.514646E-09 | -9.514646E-09 | -1.815667E-08 | -1.031964E-08 | 8.72E-09 |
| B | 1.336864E-13 | 1.336864E-13 | -2.488991E-13 | -1.081794E-13 | -2.71E-13 |
| C | -4.722253E-18 | -4.722253E-18 | 2.824306E-17 | 6.909628E-18 | 1.07E-17 |
| D | 1.120165E-22 | 1.120165E-22 | -4.697303E-21 | -3.648077E-22 | -6.07E-22 |
| E | -1.895395E-27 | -1.895395E-27 | 3.415362E-25 | 9.693996E-27 | 1.40E-26 |
| F | 1.489410E-32 | 1.489410E-32 | -9.509214E-30 | -1.380442E-31 | -1.10E-31 |
| SURFACE | 61 | 63 | | | |
| K | 0 | 0 | | | |
| A | -2.45E-08 | 4.37E-08 | | | |
| B | 6.62E-13 | -8.96E-13 | | | |
| C | -1.32E-17 | 4.21E-17 | | | |
| D | 6.68E-22 | -3.88E-21 | | | |
| E | -1.47E-26 | 2.01E-25 | | | |
| F | 1.14E-31 | -3.84E-30 | | | |

Table 7: Design data

| SURFACE | RADIUS | THICKNESS | MATERIAL | INDEX | SEMI DIAM. |
|---------|------------|-----------|------------------|----------|------------|
| 0 | ∞ | 32.0000 | | | 65.50 |
| 1 | ∞ | 0.0000 | | | 80.45 |
| 2 | 361.5503 | 30.0063 | SiO ₂ | 1.560318 | 83.87 |
| 3 | 3766.1854 | 29.9775 | | | 86.87 |
| 4 | -313.0243 | 17.3177 | SiO ₂ | 1.560318 | 90.72 |
| 5 | -211.2930 | 182.7697 | | | 93.19 |
| 6 | -709.0001 | 29.1631 | SiO ₂ | 1.560318 | 120.83 |
| 7 | -255.7121 | 13.1321 | | | 122.28 |
| 8 | 261.1325 | 45.4463 | SiO ₂ | 1.560318 | 118.65 |
| 9 | -728.3260 | 29.9790 | | | 116.70 |
| 10 | -209.1405 | 18.3161 | SiO ₂ | 1.560318 | 113.35 |
| 11 | -2675.8307 | 4.7872 | | | 113.10 |
| 12 | 421.7508 | 25.2987 | SiO ₂ | 1.560318 | 112.42 |
| 13 | -5576.5014 | 21.4392 | | | 111.29 |
| 14 | ∞ | 355.5491 | | | 103.93 |
| 15 | 249.8044 | 71.3667 | SiO ₂ | 1.560318 | 163.42 |
| 16 | -4441.8089 | 32.5158 | | | 161.31 |
| 17 | 247.2422 | 37.4261 | SiO ₂ | 1.560318 | 135.08 |
| 18 | 797.4045 | 43.7199 | | | 130.81 |
| 19 | 665.9047 | 30.0078 | SiO ₂ | 1.560318 | 108.60 |
| 20 | 318.3673 | 120.0233 | | | 96.83 |
| 21 | ∞ | 9.9881 | | | 79.40 |
| 22 | ∞ | -100.0079 | Mirror | | 122.85 |
| 23 | -145.3105 | -45.0039 | SiO ₂ | 1.560318 | 107.21 |
| 24 | -705.3999 | -7.6524 | | | 104.90 |
| 25 | -149.2286 | -15.0000 | SiO ₂ | 1.560318 | 100.69 |
| 26 | -107.5358 | -125.6003 | | | 91.50 |
| 27 | 398.2665 | -15.0000 | SiO ₂ | 1.560318 | 101.84 |
| 28 | 419.3212 | -44.0802 | | | 104.16 |
| 29 | 398.6744 | 44.0802 | Mirror | | 107.66 |
| 30 | 419.3212 | 15.0000 | SiO ₂ | 1.560318 | 104.16 |
| 31 | 398.2665 | 125.6003 | | | 101.84 |
| 32 | -107.5358 | 15.0000 | SiO ₂ | 1.560318 | 91.50 |
| 33 | -149.2286 | 7.6524 | | | 100.69 |
| 34 | -705.3999 | 45.0039 | SiO ₂ | 1.560318 | 104.90 |
| 35 | -145.3105 | 100.0079 | | | 107.21 |
| 36 | ∞ | 103.9571 | | | 130.84 |
| 37 | ∞ | -33.2893 | | | 99.43 |
| 38 | ∞ | 20.0000 | | | 210.81 |
| 39 | 250.9147 | 31.5356 | SiO ₂ | 1.560318 | 101.23 |
| 40 | -1057.0829 | 21.3930 | | | 102.52 |
| 41 | 202.0288 | 47.3927 | SiO ₂ | 1.560318 | 111.71 |
| 42 | -941.7186 | 197.8094 | | | 110.48 |

| | | | | | |
|----|------------|-----------|------------------|----------|--------|
| 43 | -88.9067 | 15.0000 | SiO ₂ | 1.560318 | 72.67 |
| 44 | -573.5619 | 23.1569 | | | 88.88 |
| 45 | -142.4338 | -23.1569 | Mirror | | 89.38 |
| 46 | -573.5619 | -15.0000 | SiO ₂ | 1.560318 | 88.88 |
| 47 | -88.9067 | -197.8094 | | | 72.67 |
| 48 | -941.7186 | -47.3927 | SiO ₂ | 1.560318 | 110.48 |
| 49 | 202.0288 | -11.3868 | | | 111.71 |
| 50 | ∞ | -9.9896 | | | 92.32 |
| 51 | -1057.0829 | -31.5356 | SiO ₂ | 1.560318 | 102.52 |
| 52 | 250.9147 | -20.0000 | | | 101.23 |
| 53 | ∞ | 209.4519 | Mirror | | 135.07 |
| 54 | -133.90811 | 9.4987 | SiO ₂ | 1.560318 | 97.71 |
| 55 | 406.9979 | 48.9711 | | | 119.82 |
| 56 | -523.9173 | 41.1332 | SiO ₂ | 1.560318 | 135.89 |
| 57 | -224.0541 | 29.8664 | | | 142.55 |
| 58 | 1367.6570 | 94.8234 | SiO ₂ | 1.560318 | 191.42 |
| 59 | -271.7647 | 8.1788 | | | 198.87 |
| 60 | 667.9279 | 83.6854 | SiO ₂ | 1.560318 | 232.81 |
| 61 | -808.5395 | 140.7841 | | | 233.01 |
| 62 | 286.6775 | 82.6895 | SiO ₂ | 1.560318 | 201.18 |
| 63 | -1096.4782 | 0.9668 | | | 198.76 |
| 64 | 350.5350 | 35.6242 | SiO ₂ | 1.560318 | 164.87 |
| 65 | 884.2685 | 0.9173 | | | 159.58 |
| 66 | 115.9293 | 64.9068 | SiO ₂ | 1.560318 | 108.97 |
| 67 | 412.6826 | 0.8041 | | | 99.04 |
| 68 | 57.1792 | 41.0408 | CaF ₂ | 1.501403 | 55.06 |
| 69 | 99.9106 | 10.1713 | Liquid | 1.600000 | 30.68 |
| 70 | ∞ | | | | 19.40 |

Table 8: Aspherical constants

| SURFACE | 3 | 19 | 24 | 28 | 30 |
|---------|---------------|---------------|---------------|---------------|---------------|
| K | 0 | 0 | 0 | 0 | 0 |
| A | -1.001534E-09 | -4.128786E-08 | -4.510495E-08 | 1.339665E-08 | 1.339665E-08 |
| B | 6.144615E-13 | -4.980750E-13 | 6.742821E-13 | 1.482582E-12 | 1.482582E-12 |
| C | 1.247768E-16 | 2.649167E-18 | 3.004246E-17 | -1.857530E-16 | -1.857530E-16 |
| D | -1.048854E-20 | 5.315992E-22 | 2.453737E-21 | 3.433994E-20 | 3.433994E-20 |
| E | -4.463818E-25 | -6.165935E-27 | -3.687563E-25 | -2.905941E-24 | -2.905941E-24 |
| F | 6.154983E-30 | 1.945950E-32 | -1.491146E-30 | 1.237374E-28 | 1.237374E-28 |
| SURFACE | 34 | 39 | 44 | 46 | 52 |
| K | 0 | 0 | 0 | 0 | 0 |
| A | -4.510495E-08 | -2.582589E-08 | -1.589920E-08 | -1.589920E-08 | -2.582589E-08 |
| B | 6.742821E-13 | -4.336537E-13 | 1.112204E-12 | 1.112204E-12 | -4.336537E-13 |
| C | 3.004246E-17 | 5.153775E-17 | -2.537422E-17 | -2.537422E-17 | 5.153775E-17 |
| D | 2.453737E-21 | -7.829187E-21 | -5.148293E-21 | -5.148293E-21 | -7.829187E-21 |
| E | -3.687563E-25 | 5.696031E-25 | 8.322199E-25 | 8.322199E-25 | 5.696031E-25 |
| F | -1.491146E-30 | -1.711252E-29 | -2.485886E-29 | -2.485886E-29 | -1.711252E-29 |
| SURFACE | 58 | 62 | 65 | 67 | |
| K | 0 | 0 | 0 | 0 | |
| A | -1.313863E-08 | -1.809441E-08 | -1.821041E-09 | -4.599046E-10 | |
| B | 1.817234E-14 | -2.428724E-14 | 4.495016E-13 | 3.983791E-12 | |
| C | 2.355838E-18 | 1.168088E-17 | -7.637258E-18 | -1.382332E-16 | |
| D | -1.447425E-22 | -4.545469E-22 | -1.610477E-21 | -2.858839E-21 | |
| E | 3.333235E-22 | 7.354258E-27 | 7.379400E-26 | 4.614539E-25 | |
| F | -4.355238E-32 | -4.766510E-32 | -9.483899E-31 | -1.411510E-29 | |

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CLAIMS

=====

1. Projection objective of a microlithographic projection exposure apparatus (110) for imaging a mask (124) that is disposable in an objective plane (122) of the projection objective (120; 120'; 120") on a
5 photosensitive layer (126) that is disposable in an image plane (128) of the projection objective, wherein the projection objective (120; 120'; 120") is designed for immersion operation in which an immersion liquid adjoins the photosensitive layer (126), and wherein the refrac-
10 tive index of the immersion liquid is greater than the refractive index of a medium (L5; 142; L205; LL7; LL8; LL9) that adjoins the immersion liquid on the object side,
characterized in that

the projection objective (120; 120'; 120") is designed in
15 such a way that the immersion liquid (134) is convexly curved towards the object plane (122) during immersion operation.
2. Projection objective according to claim 1, characterized in that the immersion liquid (134) directly
20 adjoins, during immersion operation, a concavely curved image-side surface (136) of an optical element (L5; L205; LL7; LL8; LL9) that is the last optical element of the projection objective (120) on the image side.

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3. Projection objective according to claim 2, characterized in that the curved image-side surface (136) is surrounded by a drainage barrier (140).
4. Projection objective according to claim 3, characterized in that the drainage barrier is designed as a ring (140) that is joined to the optical element (L5) and/or to a housing (141) of the projection objective (120').
5. Projection objective according to any one of claims 2 to 4, characterized in that the curved image-side surface (136) is spherical.
6. Projection objective according to claim 5, characterized in that the curved image-side surface (136) has a radius of curvature (R) that is between 0.9 times and 1.5 times and preferably 1.3 times the axial distance (d) between the curved image-side surface (136) and the image plane (128).
7. Projection objective according to claim 1, characterized in that an intermediate liquid (142), which is not miscible with the immersion liquid (134) and which forms a curved interface (139, 139') in an electric field, is situated during immersion operation between the immersion liquid (134) and an optical element (L5") that is the last optical element of the projection objective (120") on the image side.

8. Projection objective according to claim 7, characterized in that the intermediate liquid (142) is electrically conductive and the immersion liquid (134) is electrically insulating.
- 5 9. Projection objective according to claim 7 or 8, characterized in that the intermediate liquid (142) has substantially the same density as the immersion liquid (134).
- 10 10. Projection objective according to claim 9, characterized in that the immersion liquid (134) is an oil and the intermediate liquid (142) is water.
11. Projection objective according to any one of claims 7 to 10, characterized by an electrode (146) for generating the electric field.
- 15 12. Projection objective according to claim 11, characterized in that the electrode is an annular conical electrode (146) that is disposed between the optical element (L5") and the image plane (128).
- 20 13. Projection objective according to claim 11 or 12, characterized in that the curvature of the interface (139, 139') can be altered by altering a voltage applied to the electrode (146).

14. Projection objective according to any one of claims 7 to 13, characterized in that the interface (139, 139') between the intermediate liquid (142) and the immersion liquid (139) is at least approximately spherical.
- 5 15. Projection objective according to any of the preceding claims, characterized in that the immersion liquid forms an interface with the medium that is convexly curved towards the object plane in such a way that light rays pass the interface with a maximum angle of incidence
10 whose sine is between 0.5 and 0.98.
16. Projection objective according to claim 15, characterized in that the sine of the maximum angle of incidence is between 0.85 and 0.95.
17. Projection objective according to claim 16, characterized in that the sine of the maximum angle of
15 incidence is between 0.87 and 0.94.
18. Projection objective according to any of the preceding claims, characterized in that within any arbitrary volume within the projection objective the condition $(k^2 + l^2)/n^2 > K_0$ holds, wherein k , l , m are the three
20 direction cosines of an aperture ray, n is the refractive index within the volume with $k^2 + l^2 + m^2 = n^2$ and $K_0 = 0.95$.

19. Projection objective according to claim 18, characterized in that $K_0 = 0.85$.
20. Projection objective according to claim 2, characterized in that the maximum curvature of the image-side surface has a radius of curvature equals the product $m \cdot s$, wherein s is the axial distance between the curved image-side surface and the image plane and m is a real number between 20 and 120.
21. Projection objective according to claim 20, characterized in that m is between 40 and 100.
22. Projection objective according to claim 21, characterized in that m is between 70 and 90.
23. Projection objective of a microlithographic projection exposure apparatus for imaging a mask on a photosensitive layer that is disposable in an image plane of the projection objective, wherein the projection objective (120; 120'; 120'') is designed for immersion operation in which an immersion liquid adjoins the photosensitive layer (126),
- characterized in that
- the immersion liquid (134) forms an interface with a medium (LL9) that adjoins the immersion liquid on the object side of the projection objective, said interface be-

ing convexly curved towards the mask such that the maximum radius of curvature equals the product $m:s$, wherein s is the axial distance between the interface and the image plane and m is a real number between 20 and 120.

5 24. Projection objective according to claim 23, characterized in that m is between 40 and 100.

25. Projection objective according to claim 24, characterized in that m is between 70 and 90.

10 26. Projection objective according to any one of the preceding claims, characterized in that the projection objective (120) is a catadioptric objective that has at least two imaging mirrors (S_1 , S_2) and in which at least two intermediate images are formed.

15 27. Microlithographic projection exposure apparatus for producing microstructured components, characterized by a projection objective (120; 120'; 120'') according to any one of the preceding claims.

20 28. Method of microlithographically producing microstructured components, comprising the following steps:

a) providing a substrate (130) to which a layer (126) of a photosensitive material is at least partially applied;

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- b) providing a mask (124) that contains structures to be imaged;
 - c) providing a projection exposure apparatus comprising a projection objective (120; 120'; 120") according to any one of claims 1 to 21;
 - d) projecting at least a part of the mask (124) on a region of the layer (126) with the aid of the projection exposure apparatus.
23. Microstructured component that has been produced by a method according to claim 22.

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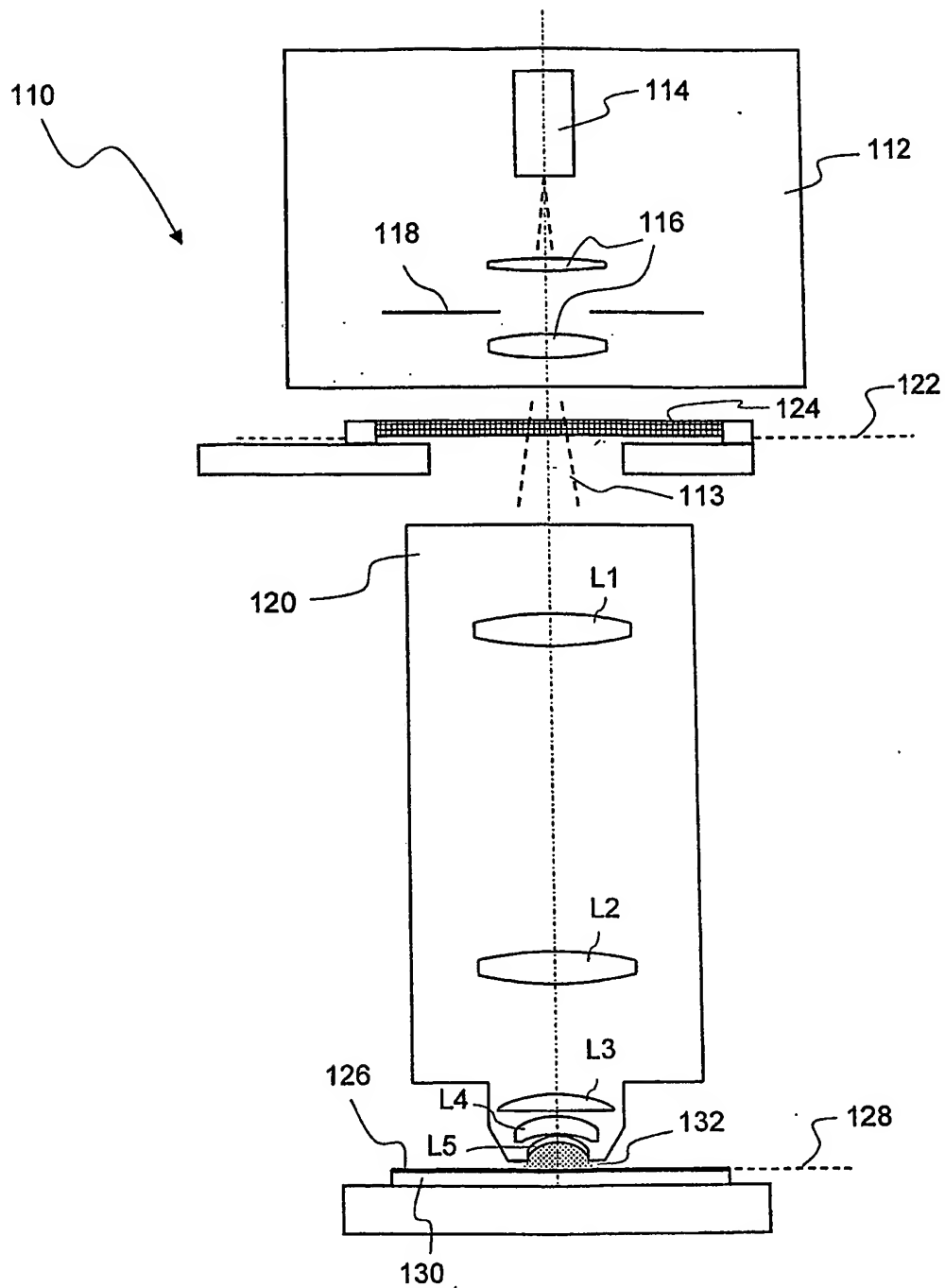


Fig. 1

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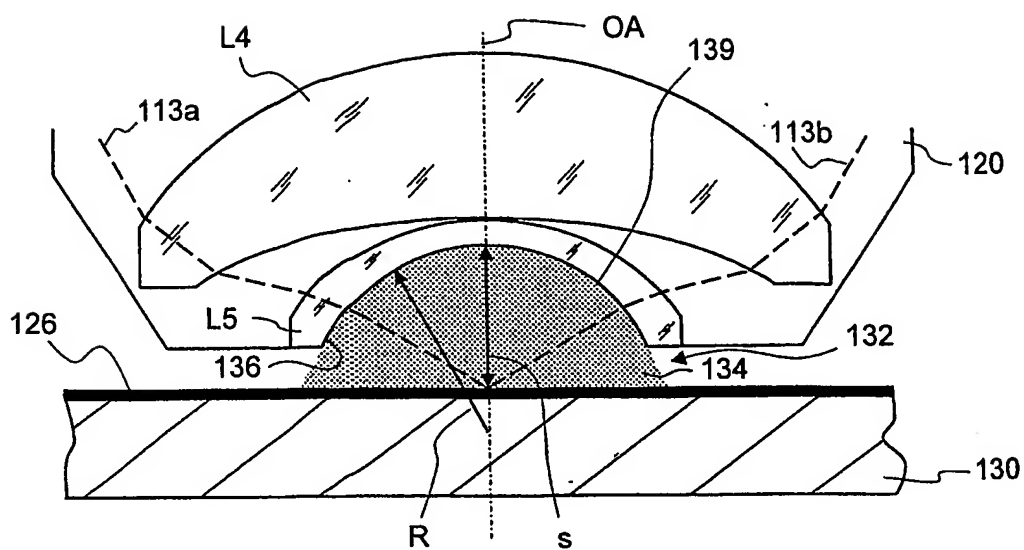


Fig. 2

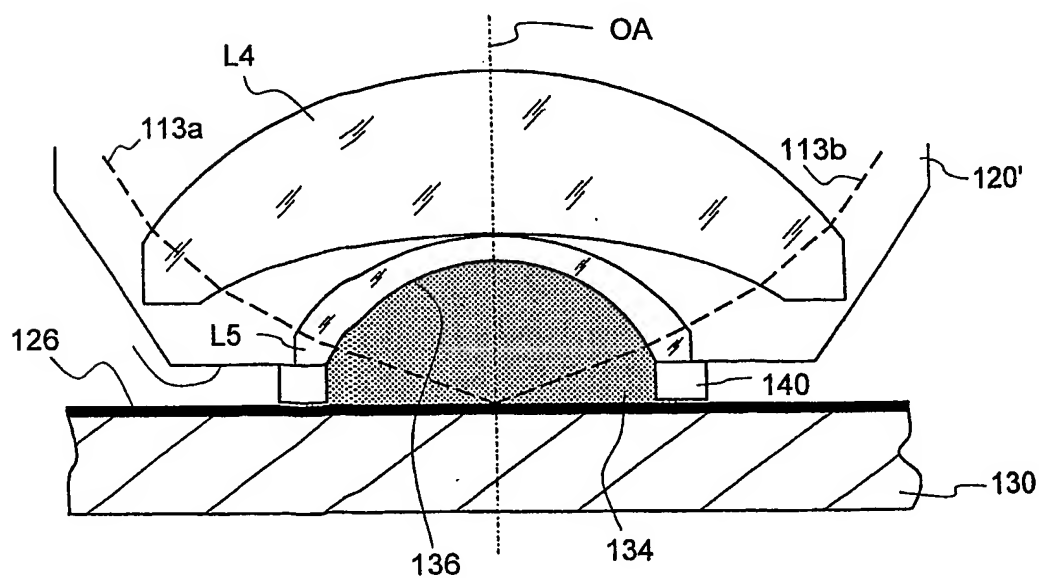


Fig. 3

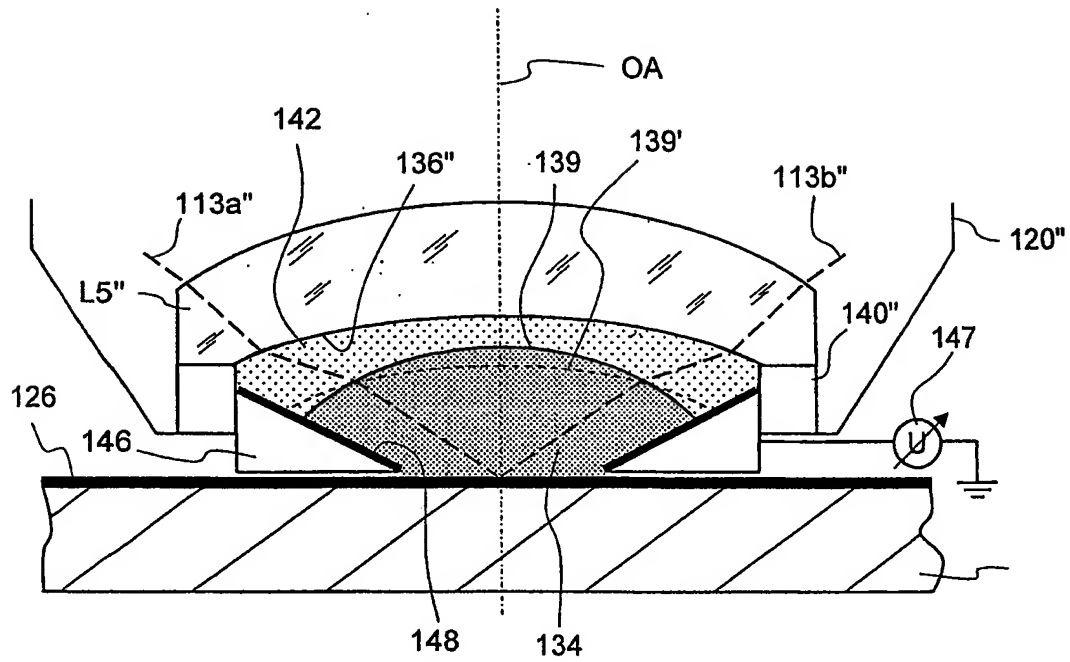
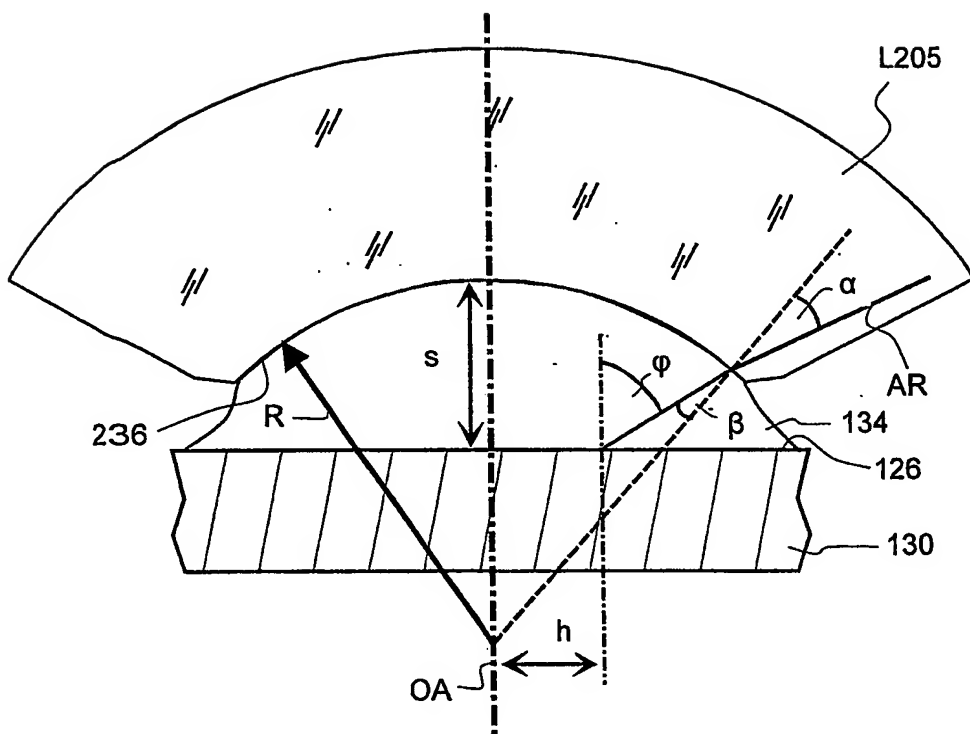


Fig. 4



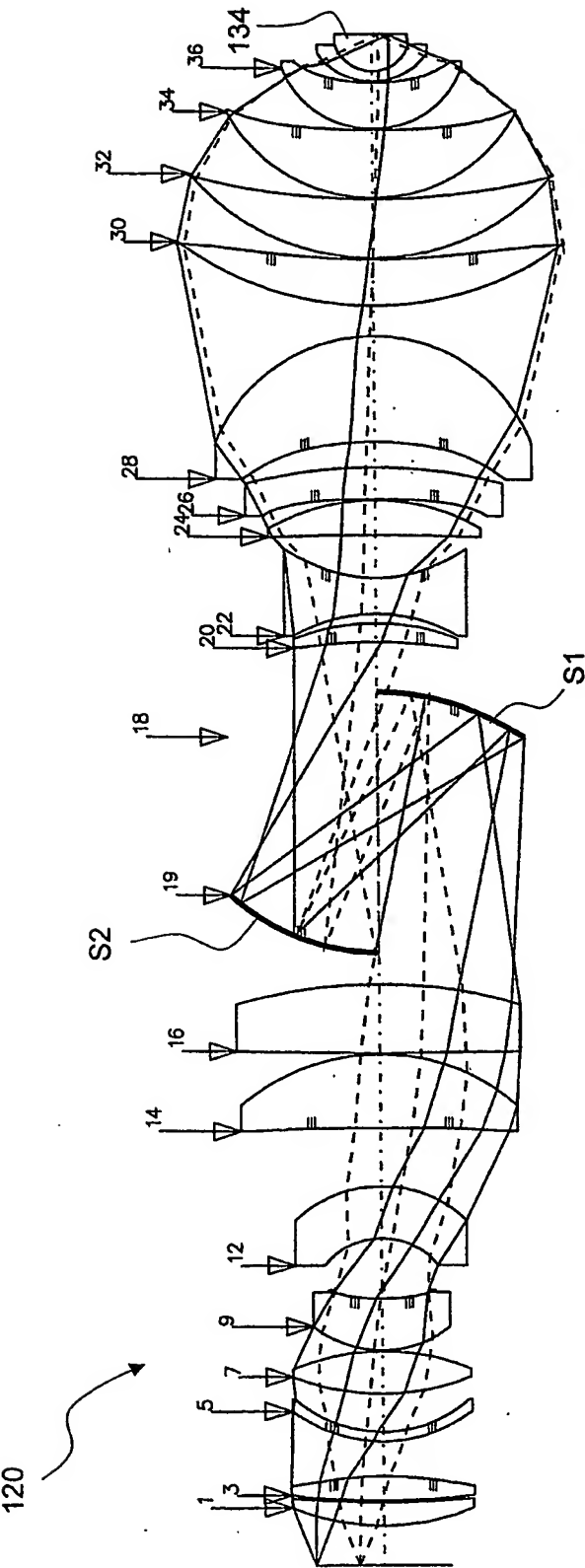


Fig. 6

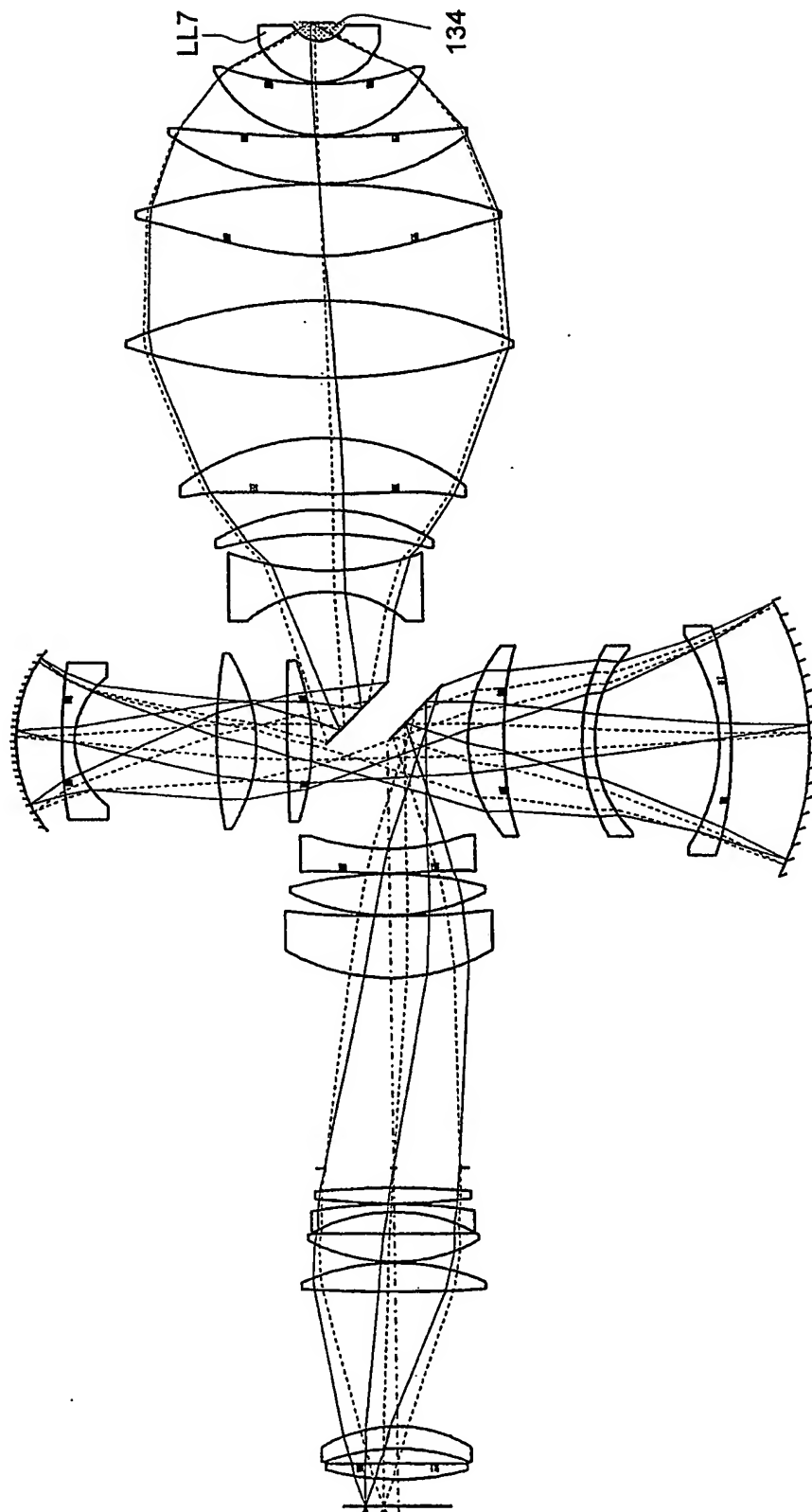


Fig. 7

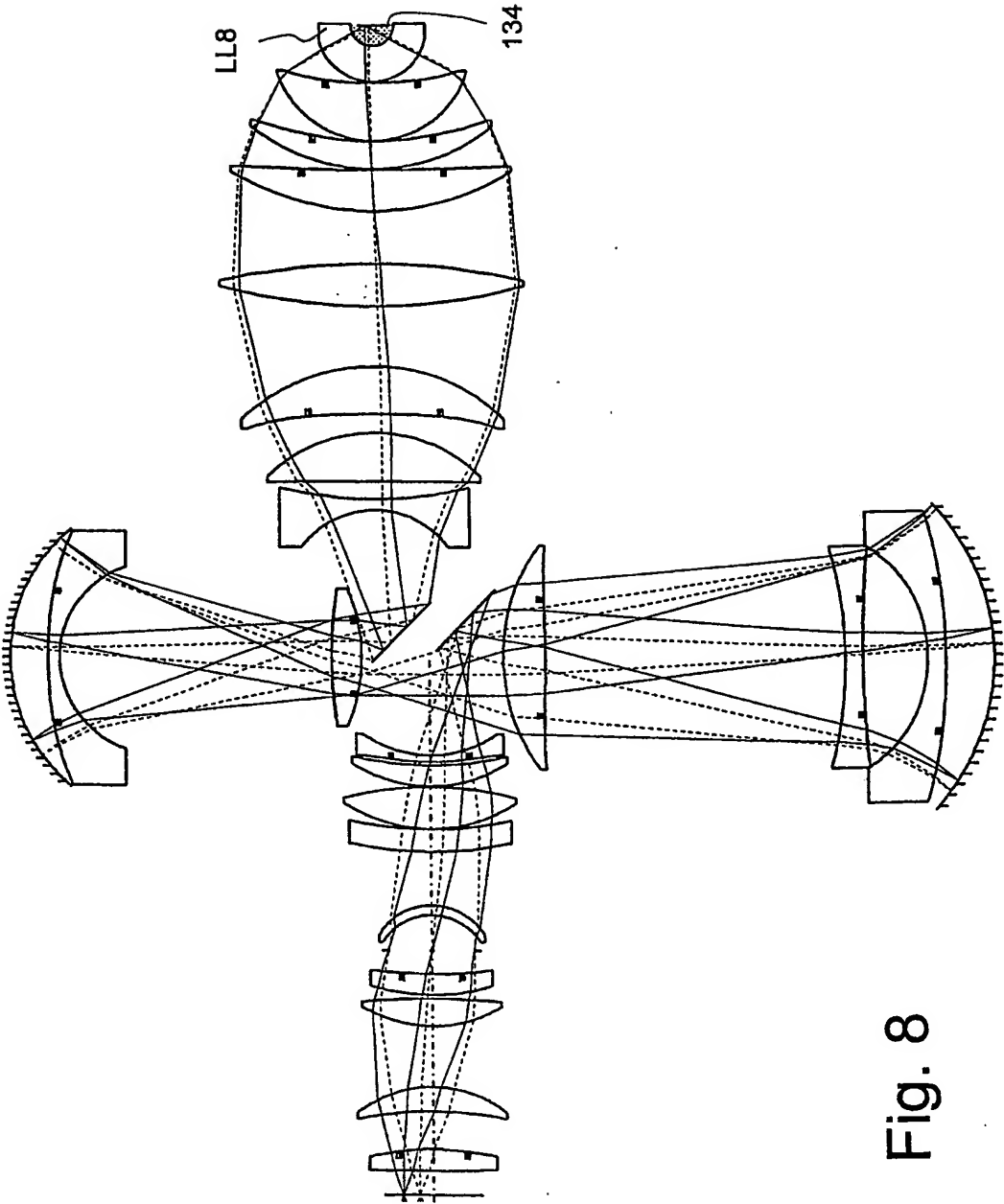


Fig. 8

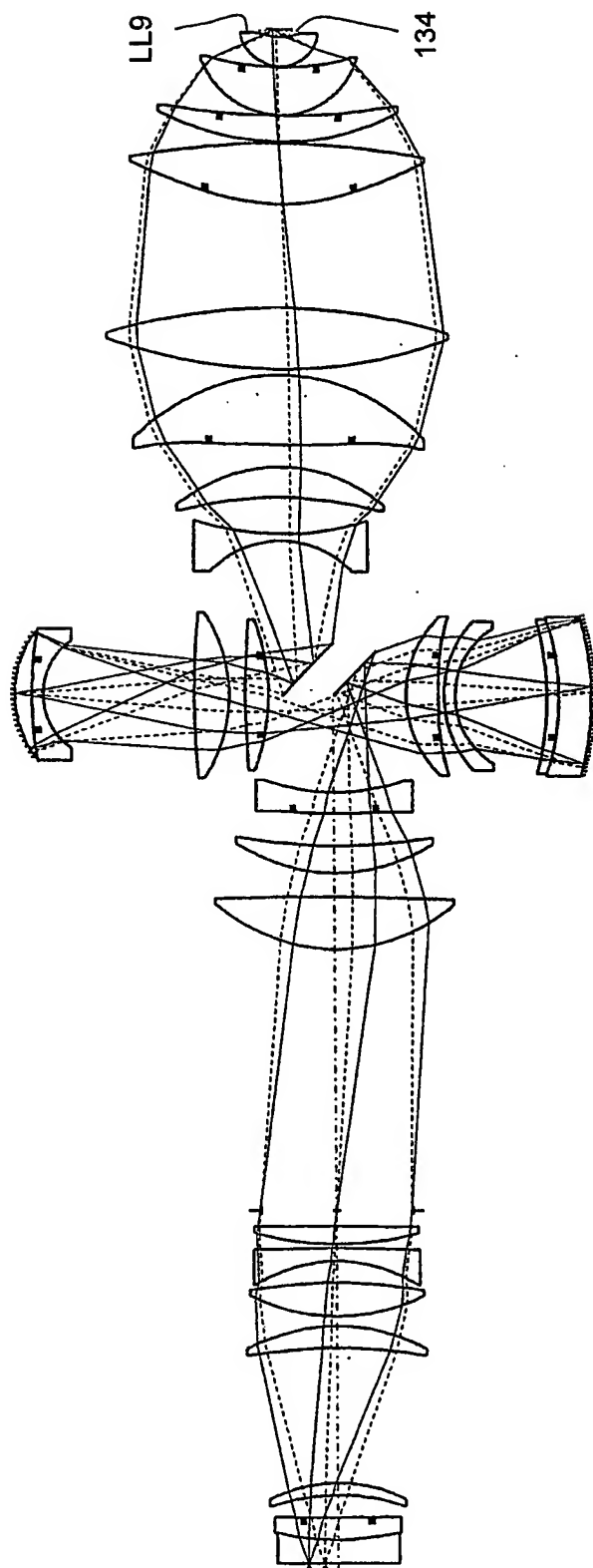


Fig. 9

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP2004/014727

| A. CLASSIFICATION OF SUBJECT MATTER IPC 7 G03F7/20 | | |
|--|---|--|
| According to International Patent Classification (IPC) or to both national classification and IPC | | |
| B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) IPC 7 G03F | | |
| Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched | | |
| Electronic data base consulted during the international search (name of data base and, where practical, search terms used) EPO-Internal, INSPEC | | |
| C. DOCUMENTS CONSIDERED TO BE RELEVANT | | |
| Category * | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
| Y X A | US 2002/163629 A1 (SWITKES MICHAEL ET AL) 7 November 2002 (2002-11-07) paragraph '0030!; figures 1a,5 | 1,2,5, 27,28 29 23 |
| Y | DAVID LAMMERS: "'Doped water' could extend 193-nm immersion litho" EETIMES ONLINE, 'Online! 28 January 2004 (2004-01-28), XP002328304 Retrieved from the Internet: URL:http://www.eetimes.com/news/latest/showArticle.jhtml?articleID=18310517> 'retrieved on 2005-05-17! cited in the application the whole document | 1,2,5, 27,28 |
| -/-- | | |
| <input checked="" type="checkbox"/> Further documents are listed in the continuation of box C. <input checked="" type="checkbox"/> Patent family members are listed in annex. | | |
| * Special categories of cited documents : <div style="display: flex; justify-content: space-between;"> <div style="width: 48%;"> <p>*A* document defining the general state of the art which is not considered to be of particular relevance</p> <p>*E* earlier document but published on or after the international filing date</p> <p>*L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>*O* document referring to an oral disclosure, use, exhibition or other means</p> <p>*P* document published prior to the international filing date but later than the priority date claimed</p> </div> <div style="width: 48%;"> <p>*T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>*X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>*Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>*G* document member of the same patent family</p> </div> </div> | | |
| Date of the actual completion of the international search 17 May 2005 | | Date of mailing of the international search report 01/06/2005 |
| Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016 | | Authorized officer Eisner, K |

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP2004/014727

| C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT | | |
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